Absolute Chronology of Deep-Sea Sediments and the Deposition of Clay on the Ocean Floor

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Abstract

An absolute chronology of deep-sea sediments on the basis of the accumulation of TiO_2 presupposes the rate of accumulation of clay to be tolerably constant with regard to time. It is here asserted that this condition is not fulfilled, because 1) the supply of fine terrigeneous matter to offshore waters will be appreciably affected by climatic changes, 2) the total amount of fine terrigeneous matter carried in suspension by sea water is deposited in about 300 years, which is a small fraction of a climatic cycle, and, consequently, 3) the amount of fine terrigeneous matter present in the sea is insufficient to act as a buffer against the variations of the supply, on account of which these variations will be reflected by almost equally great variations of the rate of accumulation.

An interesting attempt at establishing an absolute chronology of deep-sea sediments has recently been made by ARRHENIUS (1952) in a study of the cores collected from the East Equatorial Pacific by the Swedish Deep-Sea Expedition 1947—48. As asserted by KUENEN (1950), the finest terrigeneous matter carried by sea water in a very dilute suspension should bear a universal character owing to its having been carried in suspension for a very long time by ocean currents. As an indicator of the amount of fine terrigeneous matter, or lutite, present in the sediment, ARRHENIUS used titanium, which has also been suggested by WISEMAN and OVEY (1950). By determination of the radiocarbon content of a single short core obtained by means of an ordinary gravity corer, ARRHENIUS, KJELLBERG, and LIBBY (1951) determined the rate of accumulation of TiO_2 at 0.535 mg per cm^2 in 1,000 years during the last 14,200 years, making the rate of accumulation of lutite 73 mg per cm^2 in 1,000 years.

The absolute chronology given by ARRHENIUS is based on the assumption that the rate of accumulation of TiO_2 is tolerably constant with regard to time. To judge the plausibility of this assumption it appears essential to estimate the time required for an amount of lutite equal to the total amount of lutite present in the ocean to settle on the ocean floor.

ARMSTRONG and ATKINS (1950) have determined the weight of suspended matter and ash, after incineration, in the English Channel, about 10 miles south-west of the Eddystone. The average of 17 determinations during 18 months is 1.13 mg/l. The noncalcareous matter ranges between 1.57 and 0.34 mg/l, the average being 0.82 mg/l. GOLDBERG, BAKER, and FOX (1952) have determined the weight of inorganic suspended matter in San Clemente Deep off San Diego, California, down to 1,200 m, the average being 1.6 mg/l, including calcareous matter. If the observations from the English Channel are valid for ocean water, a water column of 1 cm^2 cross section in average depth should contain about 300 mg of clay. However, there can be no doubt that the load of terrigeneous matter carried by midocean sea water is considerably smaller than the load carried by the water in the English Channel.

Measurements of the Tyndall effect of midocean water samples were carried out during the Swedish Deep-Sea Expedition (JERLOV, 1953). The scattering particles being organogenic as well as minerogenic, the observations cannot be used to determine the amount of fine terrigeneous matter carried in suspension by the sea water. However, it appears possible to determine an upper limit of the amount of fine terrigeneous matter present in the water. JERLOV and KULLENBERG (1953) have measured the scattering of suspensions of quarts and felspar as a function of particle size and concentration. Using these data a reliable upper limit of the concentration of the suspension of terrigeneous matter in sea water can be computed as the concentration approximately corresponding to the total scattering, i. e., disregarding the presence of biogenic matter. To this purpose it is necessary to have an idea of the distribution of particle size of the terrigeneous matter carried in suspension by midocean sea water. A small uncertainty arises from the fact that the Tyndall effect decreases as the size of the particles falls below about 0.25 micron (STUTZ, 1930). However, as about 80 % of the eupelagic lutite has a particle size above 0.25 micron (REVELLE, 1944), the conclusions arrived at in this paper cannot be seriously affected by the uncertainty regarding particles below 0.25 micron.

As pointed out by CORRENS (1937) an attempt at computing the distribution of the size of particles suspended in sea water on the basis of the corresponding distribution in the sediment, and on the assumption that the rate of accumulation is determined by the concentration of the particles in the water and the settling velocity, as determined by Stokes' law, leads to absurd results. In fact, the fraction of the finest particles present in the sediment not approaching zero as rapidly as the square on the diameter, the analysis just indicated should lead to an overwhelming predominance of the finest particles in the water. This forces the conclusion that the finest particles are brought to the floor of the ocean more rapidly than by mere individual sinking, either by flocculation, biologic activity, turbulance, or convection in connection with the formation of bottom water. The accumulated influence of all factors might be expressed by introducing an effective settling velocity which does not approach zero as the diameter approaches zero.

The fraction of particles in the sediment with a diameter between D and $D + dD$ being $f(D) \cdot dD$, and the effective settling velocity being w, the relative distribution in the water should be expressed by $f(D) : w$, disregarding chemical transformation after deposition. Excepting the finest particles w is proportionate to D^2. As pointed out above, because $f(D)$ does not approach zero particles, this cannot be the case with the finest quickly enough to keep $f(D) : D^2$ finite as D approaches zero. Without knowing the effective settling velocity for very small particles it is not possible to compute the proportion between the weight of suspended matter above and below a very small size. However, for our present purpose it is sufficient to get a rough idea of the distribution of the size of particles carried in suspension by the water. We will, therefore, assume w to be proportionate to D^2, when $D > D_0$, and to keep a constant value corresponding to $D = D_0$, when $D < D_0$. We will carry out the computation twice, once choosing $D_0 = 0.5\,\mu$, and once choosing $D_0 = 1\,\mu$.

The distribution of particle size in North Pacific red clay (REVELLE, 1936) is given in Table 1. The mean value of $1 : D^2$ in the interval $D_1 < D < D_2$ being $1 : D_1D_2$, the relative amount of suspended matter in the

Table 1. Distribution of particle size in North Pacific red clay and the corresponding distribution in the water.

Diameter	Distribution of particle size		
	Sediment	Water	
		$D_0 = 0{,}5\,\mu$	$D_0 = 1\,\mu$
62.5 — 31.3 μ	0.35 %		
31.3 — 15.6	1.06		
15.6 — 7.81	4.56	0.02 %	0.05 %
7.81 — 3.91	10.84	0.20	0.57
3.91 — 1.95	17.02	1.27	3.60
1.95 — 0.98	19.60	5.82	16.6
0.98 — 0.49	15.22	18.1	} 79.1
0.49 — 0.24	12.06	} 74.5	
Remainder	19.32		

water is determined as $f(D) : D_1D_2$ excepting when $D < D_0$, the corresponding amount being then determined as $f(D) : D^2_0$.

It appears that 92 % resp. 79 % of the matter carried in suspension by midocean water has a diameter below 1 μ, if the value adopted for D_0 is 0.5 μ resp. 1 μ. In both cases the scattering determined by the Tyndall reading has to be multiplied by a coefficient not exceeding $2.0 \cdot 10^{-3}$ in order to get the weight of suspended matter in mg/l. The corresponding coefficient should be $4 \cdot 10^{-3}$ if the distribution of particle size were the same one in the suspension as in the sediment, which goes to prove that the magnitude of the coefficient is not seriously affected by our arbitrary assumptions concerning the effective settling velocity of small particles.

At 14 stations in the Equatorial Pacific (JERLOV, 1953) the mean value of the scattering in the whole water column varies between 20 and 47 km^{-1}, giving a medium content of suspended matter of 0.056 mg/l, including fine organic matter (Table 2). Accordingly we get an upper limit of 21 mg lutite in a column of 1 cm² cross section at average oceanic depth. KUENEN (1950, p. 347) has estimated the average of lutite in the same water column at appr. 75 mg, without quoting his source of information.

The rate of accumulation of lutite being determined by ARRHENIUS, KJELLBERG, and LIBBY at 73 mg per cm² in 1,000 years, an amount of lutite equal to the total amount present in the ocean should be deposited in less than 300 years, the concentration of the lutite here arrived at being adopted.

The influence of climate on the agencies which transport material to the sea shall not be discussed in detail here. However, it does not appear justified to postulate that the supply of fine terrigeneous matter to the offshore waters should be substantially unaffected by climatic changes. The amount of suspended matter carried to the sea by running water per unit time will be dependent on the precipitation, as the capacity of a stream to carry suspended matter varies with the third power of the discharge, if other factors are constant. Precipitation being one of the main climatic variables, it is probable that the amount of suspended matter carried to the sea by running water will display considerable variations as

Table 2. Mean value of the scattering and mean content of suspended matter in the Equatorial Pacific.

Station	Lat.	Long.	Depth	s km⁻¹	Susp. matter
65	6°21′ N	103°42′ W	3195 m	47	0.094 mg/l
80	17°46′	126°51′	4398	27	0.054
87	8°25′	128°48′	4600	39	0.078
93	0°06′ S	135°58′	4311	30	0.060
105	7°38′	152°53′	3890	26	0.052
111	0°02′ N	153°07′	2385	23	0.046
123	15°14′	152°49′	4308	27	0.054
128	12°16′	166°48′	4830	32	0.064
133	5°00′	172°02′	5159	27	0.054
138	2°37′ S	177°45′	4770	24	0.048
143	0°09′	163°23′ E	4372	23	0.046
150	2°09′ N	146°52′	4335	22	0.044
157	2°51′	134°57′	4354	20	0.040
162	5°23′	127°48′	8175	24	0.048

[1] Depth of deepest sample is stated in the depth column.

climate changes. Another variable factor influencing the supply of suspended matter to the sea is the melting of the glaciers. The *eustatic changes of the sea-level should exercise* a considerable influence upon the supply of suspended matter to the sea due to wave erosion. Even though the greater portion of the matter carried in suspension to the coastal waters will settle on, or near, the shelf, a certain fraction of the fine particles will escape to midocean localities. There seems to be no reason why the ratio of this fraction to the total supply should not, upon the whole, be unaffected by the variations of the latter or, with other words, why the variations of the supply to the coastal waters should not be reflected by similar variations of the supply to the offshore waters.

The amount of airborne terrigeneous material precipitated into the sea by rainfall is insufficiently known, as no measurements of the weight of solid matter present in rain water have been carried out at sea. The lowest value reported seems to be 4 mg insoluble matter per liter rain water, measured in the vicinity of Königsberg (KALLE, 1947), which corresponds to a supply of 300 mg per cm² in 1,000 years. Though the corresponding amount at sea should be expected to be considerably smaller, it might play an important part. There can be no doubt that this means of supply is extremely sensitive to climatic changes affecting the surface of the earth, the heating of the atmosphere, and the atmospheric circulation, all of which influence the atmospheric transport of terrigeneous matter to the sea.

It is obvious that the ocean cannot act as a buffer against the variations of the supply of fine terrigeneous matter unless it carries a load big enough to maintain the same magnitude in spite of the variations of the supply. To make this quite clear we will carry out a simple analysis. In view of the exceedingly small concentration of lutite in ocean water it appears justified to assume the rate of accumulation of lutite on the ocean floor to be proportionate to the concentration in sea water, other factors being constant. Therefore, x denoting the total weight of lutite present in the sea, the amount of lutite settling on the ocean floor per unit time will be $x : T_0$, T_0 being a constant importing the time necessary for an amount of lutite equal to the total amount present in the sea to settle on the ocean floor. We assume the supply of fine terrigeneous matter to the sea per unit time to vary periodically as $a(1 + p \sin 2\pi t/T)$, a and p being constants ($p < 1$), t denoting the time, and T the period. Then we have

$$\frac{dx}{dt} = a\left(1 + p \sin \frac{2\pi t}{T}\right) - \frac{x}{T_0}$$

$$\frac{x}{T_0} = a\left[1 + \frac{p}{\sqrt{1 + \frac{4\pi^2 T_0^2}{T^2}}} \cdot \sin\left(\frac{2\pi t}{T} - \varphi\right)\right]$$

$$tg\,\varphi = \frac{2\pi T_0}{T}$$

Hence the quote of maximum and minimum rate of accumulation of lutite during a period will be

$$q = \left(\sqrt{1 + \frac{4\pi^2 T_0^2}{T^2}} + p\right) : \left(\sqrt{1 + \frac{4\pi^2 T_0^2}{T^2}} - p\right)$$

whilst the quote of maximum and minimum supply of lutite to the ocean has been assumed to be $q_0 = (1 + p) : (1 - p)$. Choosing, by way of example, $q_0 = 4$, we get $q = 1.2$, 2.2, and 3.5 resp., if $T_0 : T = 1$, $^1/_4$, and $^1/_{16}$. Accordingly, the ocean is able to eliminate the variations of the supply very effectively if the time T_0 is equal to, or exceeds, the period T of the variations of the supply, or, with other words, if the fractional part of the total amount of suspended terrigeneous matter which is deposited per unit time does not exceed $1 : T$ very much. If the fraction deposited per unit time is greater, the rate of deposition displays variations approaching the variations of the supply, at the same time as the time lag decreases from about a quarter of a period to zero.

In the case of fine terrigeneous matter we have found that T_0 is about 300 years, whereas the length of the climatic cycles has a magnitude of at least 30,000 years. Consequently the variations of the supply of fine terrigeneous matter to the sea, accompanying climatic changes, will be reflected by almost simultaneous and equally great variations of the rate of accumulation of clay on the ocean floor. Therefore, it does not appear warranted to base an absolute chronology of deep-sea sediments on the assumption of a constant rate of accumulation of clay on the ocean floor.

REFERENCES

ARMSTRONG, F. A. J., and ATKINS, W. R. G., 1950: The suspended matter of sea water. *Journ. Marine Biol. Assoc.*, **29**, 139.

ARRHENIUS, G., 1952: Sediment cores from the East Pacific, *Reports of the Swedish Deep Sea Expedition*, **5**.

ARRHENIUS, G., KJELLBERG, G., and LIBBY, W. F., 1951: Age determination of Pacific chalk ooze by radiocarbon and titanium content. *Tellus*, **3**, 222.

CORRENS, C., 1937: Die Sedimente des Äquatorialen Atl. Ozeans. *Wiss. Erg. d. D. Atl. Exp.*, **3**, 135.

GOLDBERG, E. D., BAKER, M., and FOX, D. L., 1952: Microfiltration in oceanographic research. *Journ. of Marine Research*, **11**, 194.

JERLOV, N. G., 1953: Particle distribution in the ocean. *Reports of the Swedish Deep Sea Expedition*, **3**, 73; Appendix, Table 1.

JERLOV, N. G., and KULLENBERG, B., 1953: The Tyndall effect of uniform minerogenic suspensions. *Tellus*, **5**, .

KALLE, K., 1947: *Der Stoffhaushalt des Meeres*. Leipzig.

KUENEN, PH., 1950: *Marine Geology*. New York and London.

REVELLE, R., 1944: Marine bottom samples collected in the Pacific Ocean by the Carnegie on its seventh cruise. *Carnegie Inst. Wash. Publ.*, No. 556.

STUTZ, G. F. A., 1930: The scattering of light by dielectrics of small particle size. *Journal Franklin Institute*, **210**, 67.

WISEMAN, J. D. H., and OVEY, C. D., 1950: Recent investigations on the deep-sea floor. *Proc. of the Geol. Ass.*, **61**, 28.

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